

Assessment of the Severe Geomagnetic Storm on May 10-11, 2024 Effects on the Geomagnetic Field and Ionosphere Over the Indonesian Region

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Abstract

The severe geomagnetic storm on May 11, 2024, is the largest space weather phenomenon in the 25th solar cycle. This paper presents the impact of that severe geomagnetic storm ($Dst = -412$ nT) on the geomagnetic field and ionosphere over Indonesia. Additionally, it examines geoelectric disturbances generated during the storm and disruptions to HF radio communication in Indonesia. The study uses geomagnetic field data (HDZ) and ionospheric data (f_oF_2) from Pontianak and Kupang, averaged minutely and hourly. The results indicate that the geomagnetic storm on May 11th, 2024 caused geomagnetic disturbances with $\Delta H = -471$ nT in Pontianak and $\Delta H = -462$ nT in Kupang. These disturbances led to significant geoelectric disturbances around the region with possible induced currents. In the ionosphere, the geomagnetic storm caused negative ionospheric storms during the main phase and positive storms during the recovery phase, as observed in the f_oF_2 data from both stations. These ionospheric storms resulted in f_oF_2 disturbances (ϕ) with values ranging from -30% to 30%, lasting for 180 minutes.

Keywords:

geomagnetic storm, interplanetary magnetic field, space weather, geomagnetic induced current, ionosphere

1. Introduction

The Earth was bathed in a spectacular display of auroras in May 2024, a consequence of a powerful geomagnetic storm that reached a G5 classification - the highest on the geomagnetic storm scale defined by the National Oceanic and Atmospheric Administration (Kwak et al., 2024). This event, driven by a series of coronal mass ejections (CMEs) originating from an exceptionally active region on the Sun identified as AR13664 (Jaswal et al., 2024; Kontogiannis, 2024), marked the most intense geomagnetic storm since the famed Halloween Storms of 2003 (Gopalswamy et al., 2005). The storm peaked between May 10th and 11th, with the interplanetary magnetic field (IMF) indicating a sharp increase to 88 nT and a southward component of -50 nT (Hajra et al., 2024). Coupled with high solar wind density and speeds reaching 750–1450 km/s, this interplanetary state

created ideal conditions for a major geomagnetic disturbance (Liu et al., 2024). This resulted in a disturbance storm time (Dst) index of -412 nT, indicating a major geomagnetic disturbance. Since its occurrence coincided with International Mother's Day, the storm has been dubbed the "Mother's Day Storm", also known as "Gannon storm" (Grandin et al., 2024).

The impact was widespread. Auroras, typically confined to high-latitude regions, were visible as far south as Florida, the Yucatán Peninsula in Mexico, and even the Canary Islands, approximately 30 degrees from the geomagnetic equator (Grandin et al., 2024). This stunning visual spectacle, however, was accompanied by disruptions to radio communications and the Global Navigation Satellite Systems (GNSS). While no major power grid failures were reported, the storm served as a potent reminder of the potential for extreme geomagnetic storms to disrupt our technology-dependent world (Hapgood, 2011; Riley et al., 2018; Ishii et al., 2024). While the most dramatic effects of geomagnetic storms are often observed at high latitudes, low-latitude regions are not immune to their influence. The May 2024 storm provided compelling evidence of this influence, with au-

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roras visible in regions far closer to the equator than usual. This highlights the fact that even at low latitudes, geomagnetic storms can cause significant disruptions. Satellites experienced enhanced atmospheric drag that shortened their lifetime (**Parker and Linares, 2024**) while their operations could be disrupted, affecting communication, navigation, and Earth observation systems worldwide. Increased radiation levels during strong geomagnetic storms pose risks to astronauts and passengers on high-altitude flights.

In the ionosphere, geomagnetic storms can cause changes in plasma density, leading to either an increase or a decrease depending on the inherent characteristics. These variations are referred to as positive or negative ionospheric storms (**Horvath and Lovell, 2015; Matamba et al., 2015**), both of which can disrupt high-frequency (HF) radio communication. HF is a communication band for civil and military radio services with a frequency range of 3–30 MHz (**ITU, 2015**), which can usually extend to 2–30 MHz (**ITU, 2019**). The operating HF radio systems are usually guided by some parameters such as the Maximum Usable Frequency (MUF), Optimum Working Frequency (OWF) or Frequency Optimum Travail (FOT), Height Probable Frequency (HPF), and Lowest Usable Frequency (LUF) (**ITU, 2007; 2019**). MUF is the product of the critical frequency at the F2 ionospheric layer (f_oF2) and propagation factor ($M(3000)F2$). MUF is approximately three times that of critical frequency (**Carr, 2011**). OWF or FOT is approximately 85% MUF (**Goodman, 1992**). MUF HF radio has widespread applications in various fields, such as search and rescue operations, emergency communication, government broadcast, military communication, and radar detection. The largest impact during a storm occurs on traditional means of communication i.e. HF radio (**Wang et al., 2022**).

Specific to the Mother's Day storm, **Karan et al. (2024)** reported a poleward shift of the Equatorial Ionization Anomaly (EIA), which normally persists around 10–20 degrees north and south of the geomagnetic equator (**Balan et al., 2018**). Due to the injection of energy from the solar wind and magnetosphere, this feature changed in shape and moved up to 35° magnetic latitude. There was also evidence that EIA did merge with aurora near the tip of South America. Meanwhile, **Foster et al. (2024)** highlighted a significant increase in Total Electron Content (TEC) over the continental United States along with the auroral extension in this region. Some detectors measured a strong increase of vertical TEC up to 50 TEC units. Another form of ionospheric anomaly was also reported by **Spogli et al. (2024)** for the European region. A negative storm indicated by a decrease in ionospheric density was observed on May 11th and after the recovery phase on May 13th. A 30-TEC unit drop of the vertical TEC over the Italian Peninsula was observed on both dates. In addition to that, **Spogli et al. (2024)** also reported a drop of f_oF2 , to a very low

value of 2 MHz. At high-latitude regions, the disappearance of the F2 layer was observed during the storm, accompanied by a clear scintillation affecting the GNSS signal transmissions (**Themens et al., 2024**).

Intense storms can induce powerful electrical currents in the Earth's crust, known as geomagnetically induced currents (GICs), which can damage power grids, pipelines, and other critical infrastructure (**Pulkkinen et al., 2017; Abda et al., 2020**). The auroral electrojet (AE) is believed to play a critical role in generating GICs at high latitudes (**Ngwira et al., 2013; Ngwira and Pulkkinen, 2018**) whereas the equatorial electrojet (EEJ) is suspected to have a significant role in generating GICs at low-latitude regions during geomagnetic storms (**Nilam and Ram, 2022**). Recently, GIC measurements have been carried out in many countries at low and middle latitudes, such as Brazil (**Trivedi et al., 2007**), Spain (**Torta et al., 2012**), Australia (**Marshall et al., 2013**), China (**Liu et al., 2009**), and Japan (**Watari et al., 2009, 2021**). Depending on the location and the storm intensity, the generated GICs are typically around 10 A or lower. Interestingly, **Zawawi et al. (2020)** conducted simulations using geomagnetic field data from the Langkawi geomagnetic observatory at -2.8 dipole latitude and reported the potential presence of GICs in Malaysia. They estimated that a GIC of 7 A may appear in a 275 kV transmission transformer in Peninsular Malaysia and cause half-cycle saturation, leading to performance issues in the transformer.

Maritime regions like Indonesia face unique challenges during geomagnetic storms. Disruptions to the GNSS and radio communication can affect navigation and safety at sea. Additionally, there is evidence that coupling between the ocean and ionosphere during geomagnetic storms is possible (**Akala et al., 2020**). The increasing reliance on autonomous navigation systems in the maritime industry further emphasizes the need for robust mitigation strategies against the effects of geomagnetic storms.

In this paper, we analyze the geomagnetic field and ionospheric responses over the Indonesian region during the Mother's Day storm. Specifically, we investigate the potential of induced electric fields and disruptions to high-frequency radio communication in this maritime country.

2. Data and methods

Indonesia's location within the low-latitude region makes it a prime location for geophysical and space weather research. The ionosphere above Indonesia, influenced by the equatorial electrojet and unique atmospheric dynamics, plays a crucial role in radio wave propagation (**Abadi et al., 2021**). To support research on the ionosphere and magnetosphere over Indonesia, there are several observing stations located across this archipelago (see **Figure 1**). Previously operated by the National

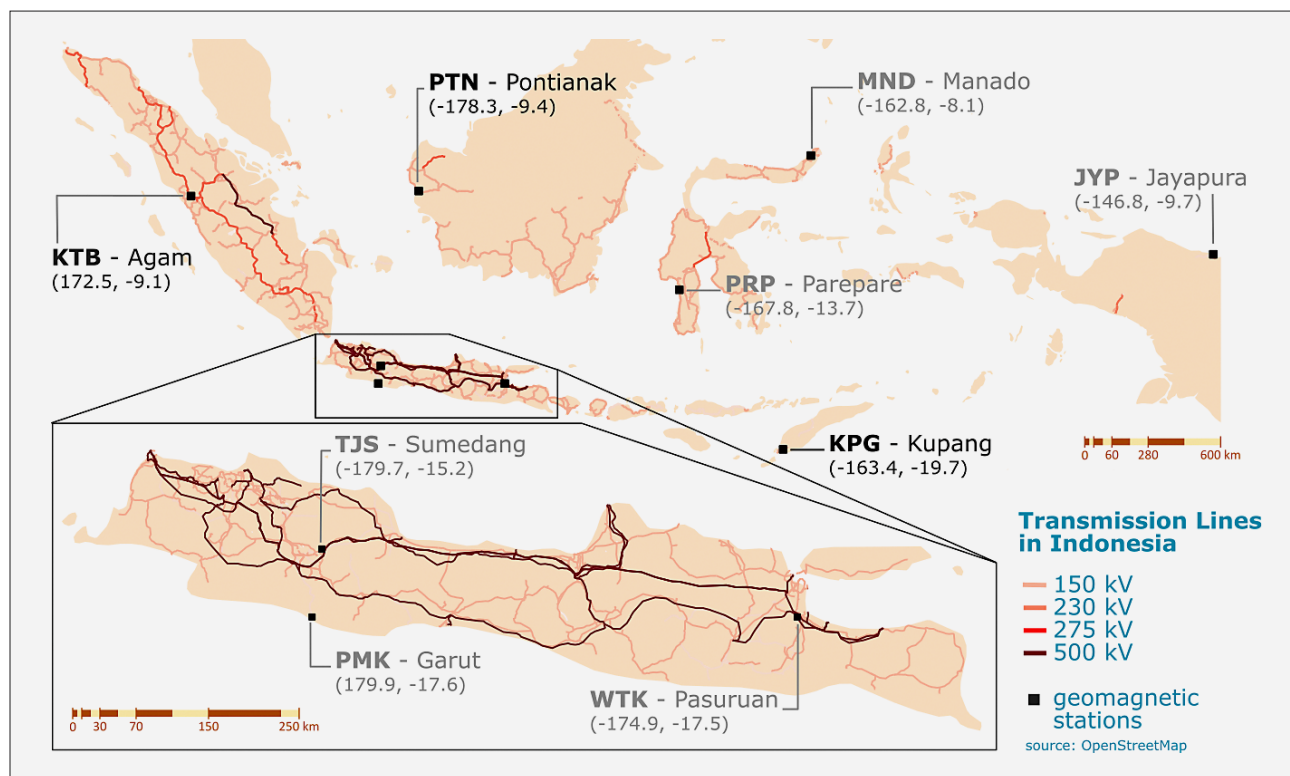


Figure 1. The map (north up) displays the locations of observing stations (squares) in Indonesia, overlaid on a network of electric transmission lines with a capacity of 150 kV or higher. Geomagnetic coordinates for each station are shown in brackets.

Institute of Aeronautics and Space (LAPAN) and now by the National Research and Innovation Agency (BRIN), the stations are equipped with some critical instruments, like a radiosonde and magnetometer.

During the Mother's Day Storm, geomagnetic and ionospheric data for further analyses were acquired from two stations, namely BRIN Pontianak (PTN, 9° S and 177°9' W magnetic or 0°2' S and 109°3' E geographic) and BRIN Kupang (KPG, 19° S and 162°9' W magnetic or 10°2' S and 123°7' E geographic). Data available on request. At these stations, a three-dimensional magnetic field (H , D , Z) was measured using fluxgate magnetometers operated at 1 second, and for the study, we averaged the data into a 1-minute sample. Actually, Agam station in Sumatera Island was operational during the storm, but the data from this station was not used in this study due to quality and validity issues. Data recorded from May 10-15 was analyzed, while the data acquired within a month before the storm was used to establish a base level in the quiet days. Meanwhile, the ionospheric monitoring was conducted using CADI ionosonde so that several important parameters, like $foF2$, could be derived. The temporal resolution of the $foF2$ data was 15 minutes.

Preprocessing of the data was done to accentuate the disturbance during the storm. At a particular time, the local disturbance was defined as the observed magnetic field subtracted by the average field strength during 5

quiet days in May 2024. The list of quiet days was obtained from the GFZ Data Services (Matzka et al., 2021). More definitely, the following equation was used to determine the disturbance:

$$\Delta H(t) = H(t) - H_{sq}(t) \quad (1)$$

where:

$\Delta H(t)$ = the local disturbance geomagnetic field,
 $H(t)$ = the observed geomagnetic field at time t ,
 $HSq(t)$ = the associated value during quiet days.

Meanwhile, preprocessing was also performed on the data produced by ionosonde at PTN and KPG. The ionogram was manually scaled to obtain the $foF2$. The median value of $foF2$ in May 2024 ($foF2_{median}$) was considered as the baseline so that the deviation from this baseline could be regarded as a disturbance due to the storm. Considering the daily variation of the $foF2$, the deviation could also be normalized by the median value to determine the relative disturbance:

$$\phi = \frac{foF2_{observed} - foF2_{median}}{foF2_{median}} 100\% \quad (2)$$

where:

ϕ = disturbed values,
 $foF2_{median}$ = the median value of $foF2$ in May 2024,
 $foF2_{observed}$ = the observed value $foF2$ in May 2024.

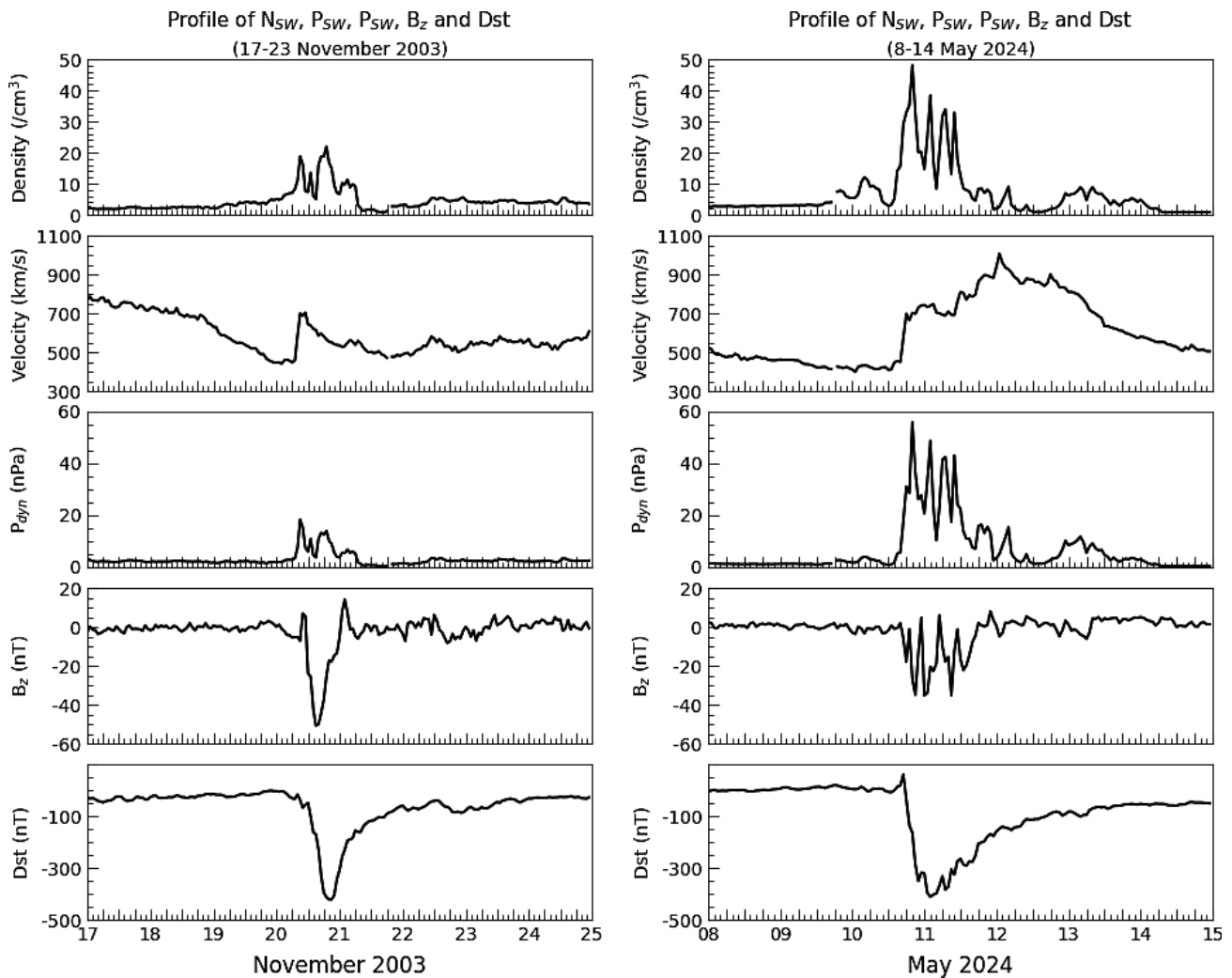


Figure 2. Graphical profile of solar wind parameters, IMF Bz component, and Dst during the geomagnetic storms on November 20, 2003 (left) and May 11, 2024 (right).

3. Geoelectric disturbance

To obtain a first-order estimate of the potential of GIC in Indonesia during the Mother's Day storm, we first estimated the electric field disturbance generated by the varying source fields from the ionosphere. Assuming the source field as a downward propagating plane wave and uniform conductivity at Earth's surface, the following relation is valid (e.g. **Viljanen, 1998**):

$$E_x(t) = \frac{1}{\sqrt{\pi\mu_0\sigma}} \int_{-\infty}^t \frac{g_y(u)}{\sqrt{t-u}} du \quad (3)$$

$$E_y(t) = -\frac{1}{\sqrt{\pi\mu_0\sigma}} \int_{-\infty}^t \frac{g_x(u)}{\sqrt{t-u}} du \quad (4)$$

where:

- μ_0 = denotes vacuum permeability = $4\pi \times 10^{-7}$ in unit (Wbr/ A. m or Wb A⁻¹ m⁻¹ or H/m),
- σ = represents the Earth's conductivity in unit S/m,
- ρ = represents the Earth's resistivity in unit W m and

$g_x(u) = dH/dt$ is the time derivative of the magnetic field along the north-south direction (V/km). The same relation applies for $g_y(u) = dD/dt$ (V/km).

Regarded as the simplest way to calculate geoelectric field due to geomagnetic changes, the plane wave method has some limitations. It does not take into account spatial variation of the ground conductivity. However, this simple method was considerably sufficient to assess the impact of geomagnetic storm in this study. The integration in **Equation 4** was in practice started 10 minutes before the time t and continues every 10 minutes. So **Equations 3** and **4** can be used to estimate the generative potential of an induced electric field.

4. Results

Intense geomagnetic storms, such as the one in May 2024, are rare events. Statistical analysis suggests that G5-level storms ($Dst < -250$ nT) occur approximately four times per solar cycle (**Tsubouchi and Omura, 2007**). Meanwhile, extreme geomagnetic events with

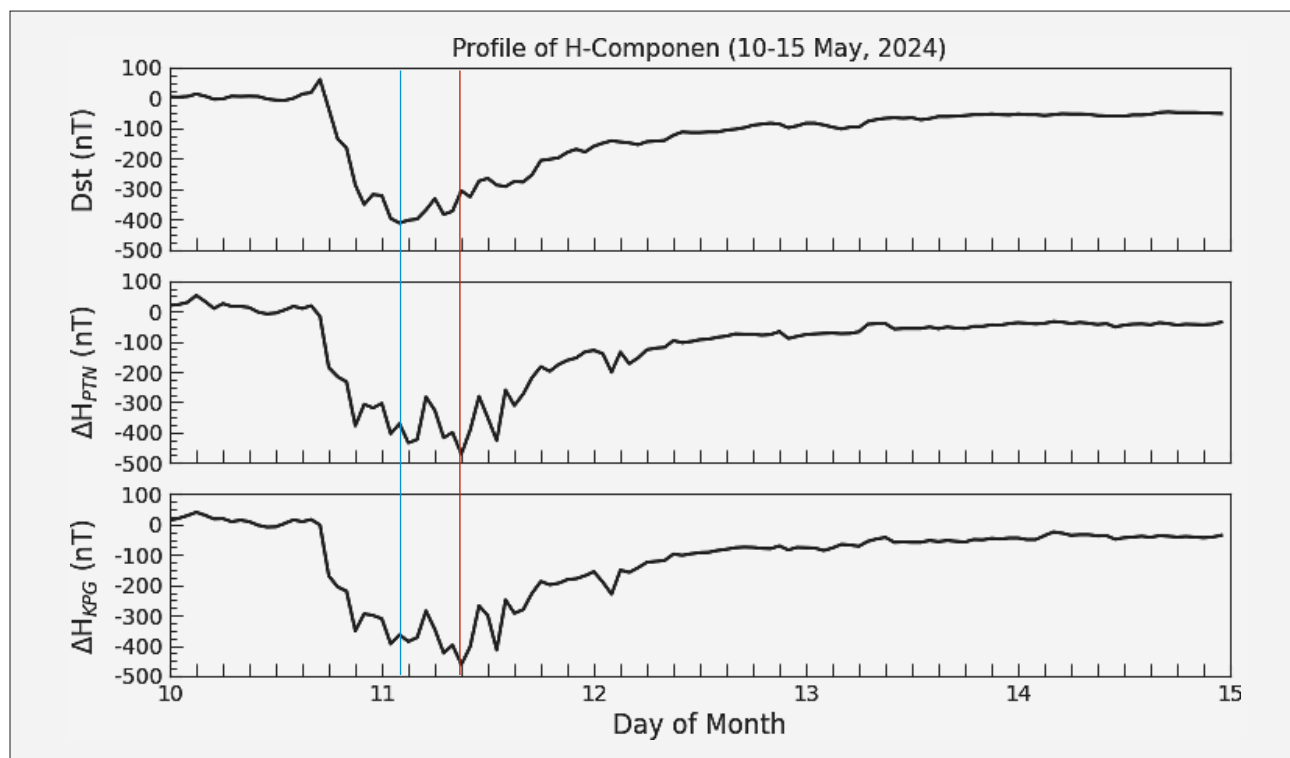


Figure 3. Graphical profile of Dst index (top), the ΔH component of the geomagnetic field from Pontianak areas (middle) and Kupang (bottom). The vertical blue line indicates the minimum Dst, while the vertical red line indicates the ΔH component from both Pontianak and Kupang reaching a minimum.

Dst values around -600 nT possibly occur once per century (Love et al., 2020; Cliver et al., 2022). However, their unpredictable nature and potential for widespread disruption underscore the importance of continuous space weather monitoring and preparedness (Schrijver et al., 2015). The last major geomagnetic storm was on November 20, 2003 ($Dst = -422$ nT). To support space weather monitoring efforts, this study compares the characteristics of the geomagnetic storms on November 20, 2003, and May 11, 2024.

Identification of the Sources of Geomagnetic Storms on November 20, 2003, and May 11, 2024

The geomagnetic storm event on November 20, 2003 ($Dst = -422$ nT at 21:00 UT) was driven by a halo CME associated to M-class flare from active region AR0501 at N00E18 on November 18, 2003, at 07:52 UT, with a travel time to Earth of 47.5 hours. Meanwhile, the geomagnetic storm on May 11, 2024 ($Dst = -412$ nT at 02:00 UT) was generated by halo CME linked to an X2.2-class flare from active region 3664, at S20W26 on May 9, 2024, at 08:45 UT, with a travel time to Earth of 32 hours. The profile of solar wind parameters and B_z before the storm (Dst index) are shown in Figure 2.

Geomagnetic Field and Geoelectric Disturbance in Indonesia

Figure 3 summarizes the severity of geomagnetic disturbances in Indonesia. In Pontianak and Kupang, ΔH

values dropped to approximately -400 nT, exhibiting fluctuations similar to those observed in the Dst index. However, the local data showed fluctuations with greater amplitude. Notably, the minimum DH values occurred approximately six hours after the minimum Dst value was recorded.

To assess geoelectric disturbances in Indonesia due to the geomagnetic storm on May 11, 2024 (Mother's Day), we can refer to the E_x and E_y values in Equations 3 and 4 using input data of the geomagnetic field components H and D from Pontianak and Kupang. Figure 4 shows the patterns of dH/dt , dD/dt , E_x , and E_y at Pontianak and Kupang. There were two episodes of geoelectric enhancements observed: one coincided with the peak of storm and another one occurred during the recovery stage (around May 12 02.00 UT). At both stations, dH/dt and dD/dt fluctuated with an amplitude of about 3 nT/s, implying geoelectric disturbances of around 10 mV/km. Smaller fluctuations were observed in the second episode. The amplitude was approximately 50% of the one in the first episode while the overall duration was only 3 hours.

Identification of Ionospheric Response and Potential HF Radio Communication Disruptions in Indonesia

To observe the impact of the Mother's Day Storm on ionospheric irregularities in Indonesia, we plotted f_oF_2 data along with the median f_oF_2 for May 2024 and cal-

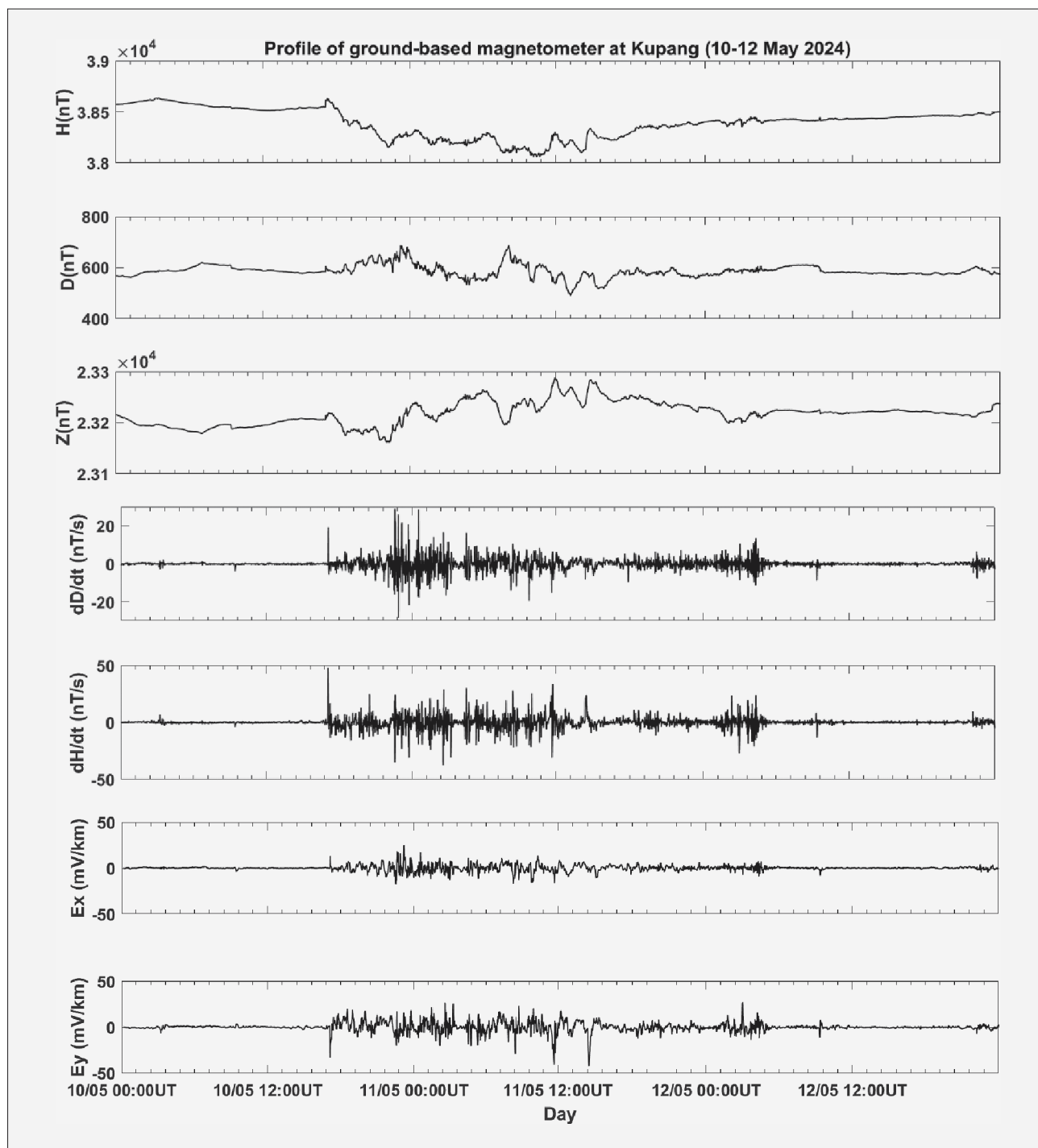


Figure 4. Profile of dH/dt , dD/dt , E_x , and E_y at Kupang on May 10–12, 2024

culated the ionospheric disturbance value (ϕ) using Equation 2. The results of the f_oF_2 data plot and the median f_oF_2 for May 2024 are shown in Figure 5.

The variation from the median value with $\pm 30\%$ of the median is shown in Figure 6.

4. Discussion

From Figure 2, several characteristics of the geospace environment's effectiveness before the geomag-

netic storms on November 20, 2003, and May 11, 2024, are summarized in Table 1. Based on this data, the geospace environment's effectiveness before the May 11, 2024 storm was more prominent compared to the November 20, 2003 storm. However, due to the stronger B_z and ΔT (time lag) values in the November 20, 2003 storm, the Dst value was more intense than in the May 11, 2024 storm. Therefore, it is believed that the behaviour of the solar wind parameters, B_z , and ΔT , were crucial factors in these geomagnetic storm events.

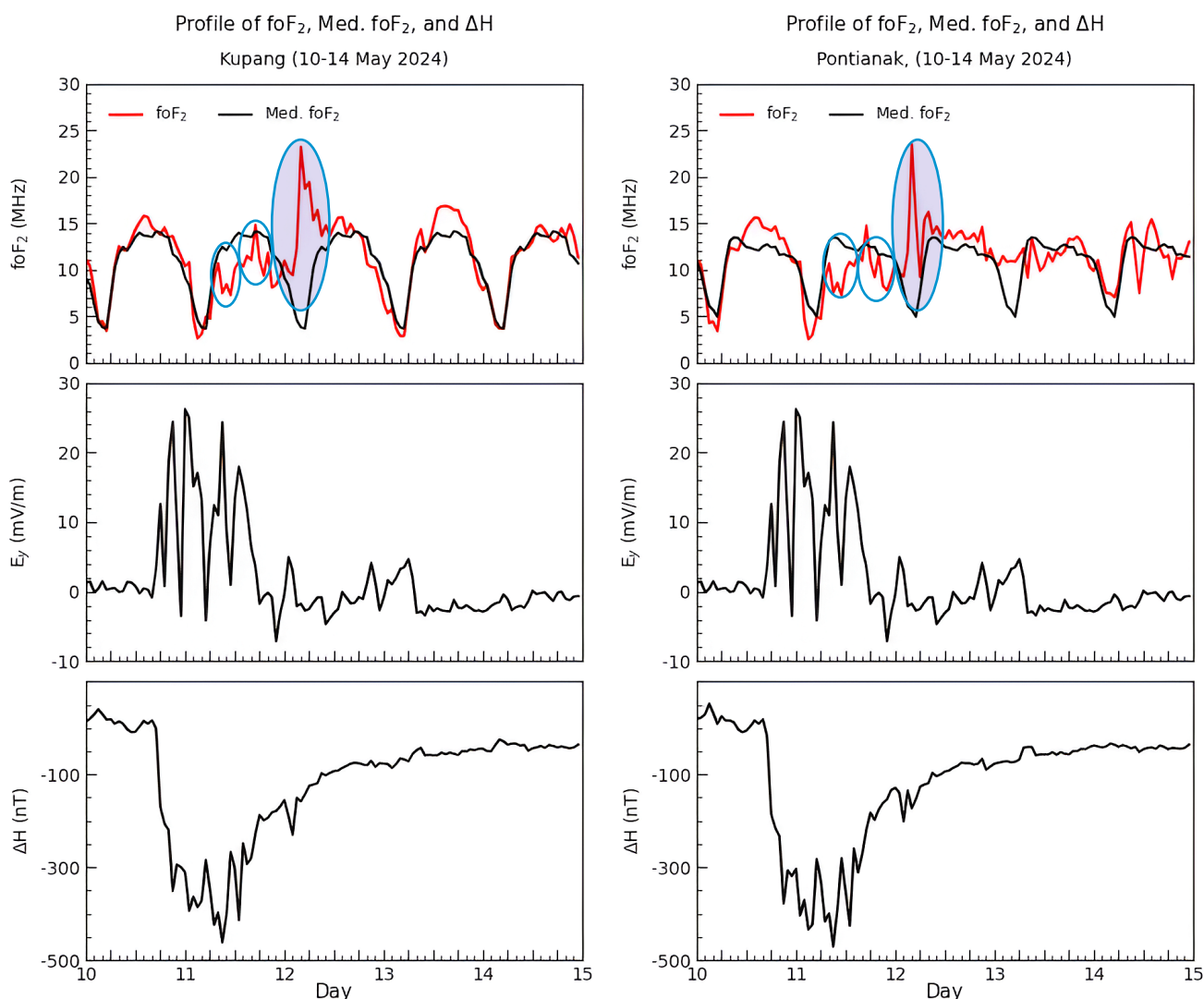


Figure 5. Graphical profile of foF_2 , Median foF_2 , E_y and DH from May 10-14, 2024 at Kupang (left) and Pontianak (right). The blue ellipse indicates the largest disturbances.

From **Figure 3**, it can be seen that geomagnetic disturbances in Indonesia caused by the geomagnetic storm on May 11, 2024, resulted in a minimum ΔH of -471 nT at KKI Kebun Raya BRIN Pontianak and a minimum ΔH of -462 nT at KSL Observatorium Nasional Timau BRIN Kupang. The minimum ΔH occurred at 08:00 UT on May 11, 2024 (or 16:00 WIB, Western Indonesian Time Zone, where WIB = UT + 7) for Pontianak and at 09:00 UT on May 11, 2024 (or 17:00 WIB, Center Indonesian Time Zone, where WITA = UT + 8) for Kupang. The geomagnetic ΔH amplitude at Pontianak and Kupang reached its minimum 7 hours after the peak of the geomagnetic storm on May 11, 2024 ($Dst = -412$ nT at 02:00 UT), possibly due to the delayed response of high-to-low latitude interaction processes (Yumoto et al., 1996). The ΔH amplitude at Pontianak was slightly greater than at Kupang, likely due to Pontianak's closer proximity to the magnetic equator, possibly experiencing a minor influence from the equatorial electrojet (EEJ). At the equator, the dynamo current causes an in-

crease in Cowling conductivity generated by the magnetospheric convection electric field, leading to an increase in the eastward current during the daytime main phase of the geomagnetic storm. This highlights the role of the EEJ current at the equator, comparable to the Auroral Electrojet (AE) in polar regions. This finding aligns with the research of Overbye (2013), Ngwira and Pulkkinen (2018), Tozzi et al. (2019), Chakrabarty (2021), and Nilam and Ram (2022).

From **Figure 4**, the amplitudes of dD/dt , dH/dt , E_x , and E_y for Pontianak (PTN) are 11.10 nT/min, 1.36 nT/min, 91.12 mV/km, and 9.45 mV/km, respectively. Meanwhile, for Kupang (KPG), the amplitudes of dD/dt , dH/dt , E_x , and E_y are 10.53 nT/min, 27.71 nT/min, 5.88 mV/km, and 29.04 mV/km, respectively. It can be seen that E_x and E_y at PTN are greater than at KPG. To further evaluate the potential for GIC in the Indonesian region, it is important to note the presence of a 500 kVA electricity distribution network across Java-Bali and Sumatra, spanning more than 100 km. The calculated in-

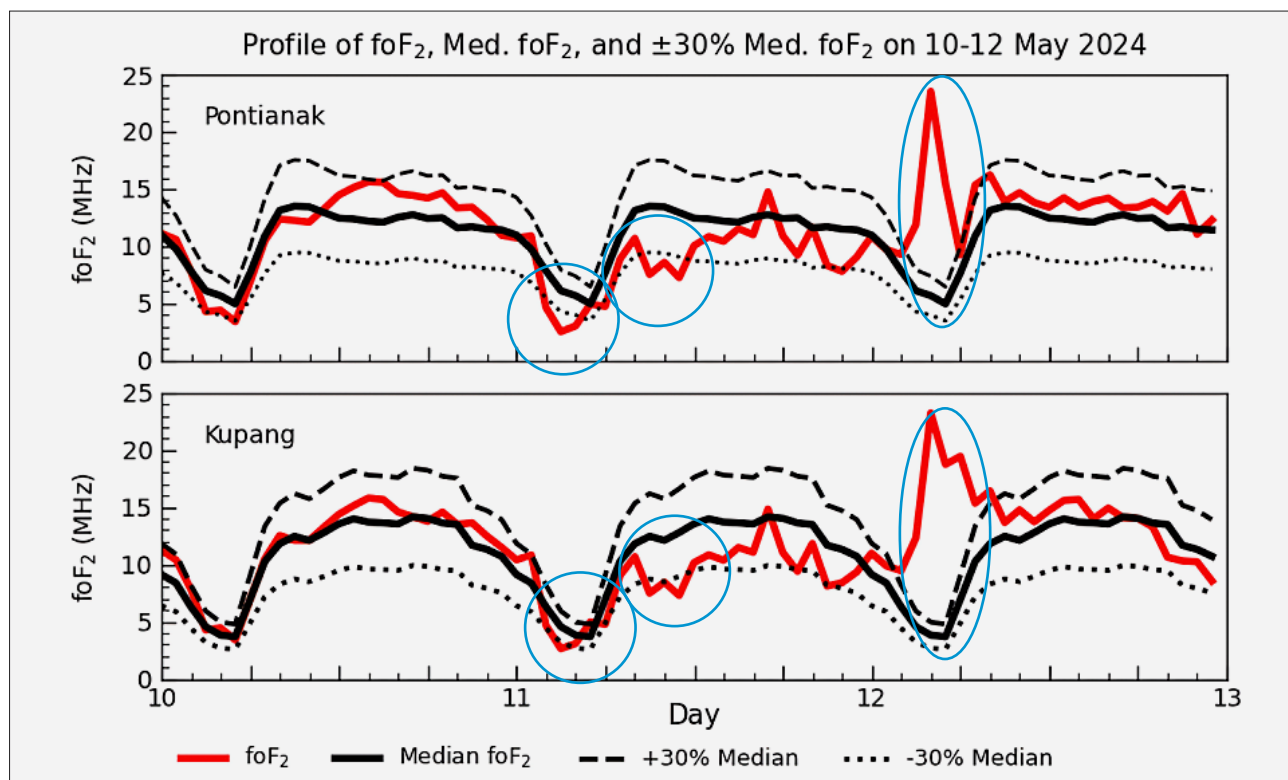


Figure 6. The profile of foF_2 data, the median, and $\pm 30\%$ of the median foF_2 value in Pontianak (top) and Kupang (bottom) from May 10 to 12, 2024. There are three regions where the value of $\phi < \pm 30\%$ of the median foF_2 value, indicated by the blue circles/ellipses

duced electric fields for Pontianak (PTN) were on the order of 91.12 mV/km and 9.45 mV/km, respectively. Meanwhile, for Kupang (KPG), the amplitudes of dD/dt , dH/dt , E_x , and E_y were 10.53 nT/min, 27.71 nT/min, 5.88 mV/km, and 29.04 mV/km, respectively. However, no significant impacts were reported.

Resilience of Indonesia's Power Grid:

With an average distribution power of 1120 MVA (MW), the maximum current carried by the 500 kV transmission line is approximately 2240 A in alternating current (AC) (Hidayat, 2021). Therefore, the estimated overload current, as an anticipated overload, is 10% of 2240 A, which is about 224 A (AC). Meanwhile, GIC is quasi-DC. To date, the exact value of GIC in Indonesia remains unknown. However, referring to the research by Zamawi et al. (2020), which simulated the maximum GIC capable of inducing half-cycle saturation in transformers, it was found that a GIC of 7 A was sufficient to trigger signs of half-cycle saturation. This finding explains why the GIC from the Mother's Day Storm did not cause disruptions or damage to Indonesia's power system.

From Figure 6, it is evident that both Pontianak and Kupang experienced a positive ionospheric storm during the main phase of the geomagnetic storm, followed by a negative storm during the recovery phase. On May 12, 2024, spread-F occurred at Pontianak (03:00 WIB or 07:00 UT) the increase in foF_2 value is about 23.52

MHz, and at Kupang (04:00 WITA or 08:00 UT) the increase in foF_2 value is about 23.22 MHz.

From Figure 6, a summary of the physical characteristics of the ionosphere in Pontianak and Kupang was obtained, and the results are presented in Table 2.

Based on Table 2, the ionospheric disturbances in Indonesia caused by the geomagnetic storm on May 11, 2024, lasted for 3 hours with a severity level of $-30\% > f > 30\%$, categorizing it as severe. The smallest foF_2 value is 2.51 MHz at 02:00 WIB on May 11, 2024 (18:00 UT on May 10, 2024) for Pontianak and 2.62 MHz at 03:00 WITA on May 11, 2024 (19:00 UT on May 10, 2024) for Kupang. Theoretically, it is known that MUF is three times foF_2 and OMF or FOT is 85% of MUF, so MUF values at PTN are about $3 \times 2.51 \text{ MHz} = 7.53 \text{ MHz}$ and OMF or FOT is about 85% of MUF = 6.4 MHz. While the MUF value at KPG is about $3 \times 2.62 \text{ MHz} = 7.86 \text{ MHz}$ and the OMF of FOT is about 85% of MUF = 6.68 MHz. These values are included in band 2 MHz – 30 MHz (ITU, 2019). However, no significant impacts on communication and navigation networks in Indonesia have been reported. Knowledge about the sources of signal interference and how to anticipate them is well understood by HF radio operators in Indonesia, and HF radio systems used in operational mode are modern communication as HF radio (Wang et al., 2022). As for satellite-based communication, operations have been effectively managed by satellite operators. This is likely

Table 1. Physical Characteristics of the Geospace Environment Before the Geomagnetic Storms on November 20, 2003 and May 11, 2024

No	Physical Characteristics	20-November-03	11-May-24
1	Flare class	M3.2	X2.2
2	Amount of Flare	1 flare on 18 November 2023 08:50 UT followed by halo CME	2 flares on 09 May 2024 Followed by halo CME
3	Linear Speed	1,660 km s ⁻¹	08.45 UT - 1280 km s ⁻¹ and 18.52 UT - 1024 km s ⁻¹
4	Kinetic Energy	3.3 × 10 ³² erg	-
5	Acceleration	-3.3 m s ⁻²	-20.6 m s ⁻²
6	Travel time	47.5 hours	32 hours
7	Dst minimum	-422 nT	-412 nT
8	Bz minimum	-50.9 nT	-35.3 nT
9	$\Delta T (B_{zmin} - Dst_{min})$	5 hours	2 hours
10	Value of N_{sw} when Dst reaching a minimum	18.8 N. cm ³	48.1 N. cm ³
11	$\Delta T (N_{swmax} - Dst_{min})$	9 hours	6 hours
12	Value of V_{sw} when Dst reaching a minimum	699 km s ⁻¹	742 km s ⁻¹
13	$\Delta T (V_{swmax} - Dst_{min})$	11 hours	2 hours
14	Value of P_{sw} when Dst reaching a minimum	18.37 nPa	55.89 nPa
15	$\Delta T (P_{swmax} - Dst_{min})$	11 hours	6 hours
16	ΔT_{Dst} onset to minimum	14 hours	11 hours

$\Delta T (B_{zmin} - Dst_{min})$ is the time lag between minimum Bz and minimum Dst , $\Delta T (N_{swmax} - Dst_{min})$ is the time lag between maximum N_{sw} and minimum Dst , $\Delta T (V_{swmax} - Dst_{min})$ is time lag between maximum V_{sw} and minimum Dst , $\Delta T (P_{swmax} - Dst_{min})$ is time lag between maximum P_{sw} , Bz and minimum Dst

Table 2. Summary of ionospheric irregularity characteristics over Pontianak and Kupang from May 10-12, 2024

No	Physical Characteristics	Values	
		Pontianak	Kupang
a	The amount of -30% Median < foF2 _{data}	3 times	2 times
b	The value of foF2 _{data} has long been in position a.	3 hours, 3 hours and 1 hour	3 hours and 1 hour
c	The time of occurrence of foF2 _{data} is at position a.	02:00-04:00 LT; 09:00-11:00 LT and 22:00 LT	09:00-11:00 LT and 19:00 LT
d	The date of occurrence of foF2 _{data} is at position a.	On May 11, 2024	On May 11, 2024
e	The amount of foF2 _{data} > 30% Median	2 times	1 time
f	The value of foF2 _{data} has long been in position e.	3 hours and 1 hour	7 hours
g	The time of occurrence of foF2 _{data} is at position e.	03:00-05:00 LT and 07:00 LT	02:00-08:00 LT
h	The date of occurrence of foF2 _{data} is at position e.	On May 12, 2024	On May 12, 2024

why the impact of the Mother's Day Storm did not significantly affect the Indonesian region.

5. Conclusions

From the discussion above, it can be concluded that the conditions and behaviours of solar wind parameters, along with B_s (B_z which is southward direction), play a critical role in determining the intensity of geomagnetic storms. Their combination is essential for the occurrence (or absence) of geomagnetic storms and also influences their intensity. Based on the case studies of two geomagnetic storm events, we conclude that the duration and

intensity of B_s are key factors that facilitate the entry of solar wind parameters into the Earth's magnetosphere.

The geomagnetic storm on May 11, 2024, caused geomagnetic disturbances with $\Delta H = -471$ nT in Pontianak (severe storm) and $\Delta H = -462$ nT in Kupang (severe storm) while the geoelectric disturbances of $E_x = 91.12$ mV/km and $E_y = 9.45$ mV/km (in Pontianak) and $E_x = 5.88$ mV/km and $E_y = 29.04$ mV/km (in Kupang) were observed. In the ionosphere, the geomagnetic storm caused negative ionospheric storms during the main phase and positive storms during the recovery phase, as observed in the foF2 data from Pontianak and Kupang. These ionospheric storms resulted in severe foF2 distur-

bances (ϕ) with values ranging from -30% to 30%, lasting for 180 minutes.

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SAŽETAK

Procjena učinaka jake geomagnetske oluje od 10. do 11. svibnja 2024. na geomagnetsko polje i ionosferu nad indonezijskim područjem

Jaka geomagnetska oluja 11. svibnja 2024. najveći je svemirski vremenski fenomen u 25. Sunčevu ciklusu. U ovome radu prikazan je utjecaj te jake geomagnetske oluje ($Dst = -412$ nT) na geomagnetsko polje i ionosferu iznad Indonezije. Dodatno, ispituju se geoelektrični poremećaji nastali tijekom oluje i poremećaji HF radiokomunikacije u Indoneziji. Studija upotrebljava podatke o geomagnetskome polju (HDZ) i podatke o ionosferi (f_oF_2) iz Pontianaka i Kupanga, izračunane u prosjeku po minuti i po satu. Rezultati pokazuju da je geomagnetska oluja 11. svibnja 2024. uzrokovala geomagnetske poremećaje s $\Delta H = -471$ nT u Pontianaku i $\Delta H = -462$ nT u Kupangu. Ti su poremećaji doveli do znatnih geoelektričnih potresa oko regije s mogućim induciranim strujama. U ionosferi je geomagnetska oluja uzrokovala negativne ionosferske oluje tijekom glavne faze i pozitivne oluje tijekom faze oporavka, kao što je primijećeno u f_oF_2 podacima s obiju postaja. Ove ionosferske oluje rezultirale su poremećajima f_oF_2 (ϕ) s vrijednostima u rasponu od -30% do 30% u trajanju od 180 minuta.

Ključne riječi:

geomagnetska oluja, međuplanetarno magnetsko polje, svemirsko vrijeme, geomagnetska inducirana struja, ionosfera

Author's contribution

Anwar Santoso (Doctoral Student of Physics, first author, magnetosphere and ionosphere) provided analyses and interpretations on the geomagnetic storm and its effect on geomagnetic field and ionosphere. **Sismanto** (Promotor, co-author, Earth electric field-Physics) provided lithospheric potential on geomagnetic induced current analysis. **Rhorom Priyatikanto** (Co-Promotor-1, Doctor of Astronomy and Astrophysics, Co-author, Astronomy and Astrophysics) provided solar activity analyses. **Eddy Hartantyo** (Co-Promotor-2, Doctor of Physics, Co-author, Physics) provided geological analyses. **Emanuel Sungging Mumpuni** (Doctor of Astronomy and Astrophysics, Co-author, Astronomy and Astrophysics) provided solar activity interpretations. **La Ode Muhammad Musafar Kilowasid** (Doctoral Student of Physics, co-author, magnetosphere and ionosphere) provided ionosphere and geomagnetic field data and interpretation at KKI Kebun Raya BRIN Pontianak. **Abdul Rahman** (Doctor of Astronomy and Astrophysics, Co-author, Astronomy and Astrophysics) provided ionosphere and geomagnetic field data interpretation at KSL Observasi Nasional Timau BRIN Kupang. **Fitri Nuraeni** (Master of Physics, Co-author, magnetosphere and ionosphere) provided analyses and interpretations of the geomagnetic data. **Siska Filawati** (Master of Physics, Co-author, magnetosphere and ionosphere) contributed in geomagnetic data processing and figure generation. **Erlansyah** (Master of Physics, Co-author, magnetosphere and ionosphere) contributed on ionospheric data interpretation. **Dadang Nurmali** (Bachelor of Physics, Co-author, magnetosphere and ionosphere) contributed on ionosphere data processing. All authors have read and agreed to the published version of the manuscript.